MICROSTIMULATORS AND MICROTRANSDUCERS FOR FUNCTIONAL NEUROMUSCULAR STIMULATION

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Abstract

We are developing a new class of implantable electronic devices for a wide range of neural prosthetic applications. Each implant consists of a microminiature capsule that can be injected into any desired location through a 12 gauge hypodermic needle. Multiple implants receive power and digitally-encoded command signals from an RF field established by a single external coil. The first two types of implant that we have made were single-channel microstimulators equipped with either a capacitor-electrode or an internal capacitor that stores charge electrolytically and releases it upon command as current-regulated stimulation pulses. We are also working on implants equipped with bidirectional telemetry that can be used to record sensory feedback or motor command signals and transmit them to the external control system.

In this quarter, we completed long term testing of BIONs both in vivo and in vitro. Passive BIONs and negative control implants were removed from both the 6 month and 13 month chronic cats at post mortems. The BIONs were well-anchored into the muscle sites in which they had been implanted and the surrounding tissue showed no signs of inflammation or undue thickening of connective tissue. Histopathological evaluation is underway. The last BION under continuous active testing in vitro was removed at 286 days after an abrupt failure caused by mechanical damage. The electrodes showed no signs of deterioration in the scanning electron microscope.

Chronic Animal Testing at Queen's University

The biocompatibility of injectable microstimulators in glass packaging has been evaluated previously in relatively short trials of up to two months. In this quarter, we have extended this testing series by sacrificing two sets of longer-term animals in which devices and control materials were inserted for 6 months and 13 months. The protocols used for these tests were designed and implemented under the guidelines of Good Laboratory Practices. Thus special care was taken with documentation, evaluative methods and calibration of laboratory tools. Animals were subject to detailed necropsy carried out by a licensed veterinary pathologist.

Each animal in the series was implanted with 5 devices, including two glass microstimulators, one glass microstimulator coated with a silicon sheath, a USP specified polyethylene rod (negative control) and a filled silicon tube of the same dimensions as the microstimulator. See Table 1. The placement sites included both paraspinal muscles and tibialis anterior. The additional hindlimb muscle site was chosen because it was considered possible that the tibialis anterior muscle would be used more actively and might show a different pattern of reaction. Three cats were initially implanted in each group. However, one animal in the six-month survival group had to be sacrificed prematurely at four months because it had an undetected but longstanding uterine and kidney infection that was believed to predate the time of implantation but worsened over the subsequent period. Evidence for the preexisting nature of the condition was obtained at autopsy. The cat had been reported to have a distended abdomen at the time of the implantation that was attributed to fat, but was later found to have an abnormal, swollen uterus that weighed more than 1 kg, and presumably accounted for the long-standing and documented abdominal distension. All of the remaining animals were healthy throughout the study and had no detectible abnormalities in their organ systems at the time of necropsy.

The sites of implantation were well-healed and the muscle around the devices showed no obvious signs of inflammation or reddening. The BIONs could be seen through the thin, semitransparent encapsulation. The microstimulators adhered strongly to their site of placement because of tissue ingrowth into the grooves separating the tantalum and iridium electrodes from the shaft of the glass capsule. The connective tissue strands had to be cut or broken, whereupon the device slide freely from its sheath. The muscle around the device was removed and bisected at the midpoint of the device site. One half of the muscle was sent for histopathological analysis to CVD laboratories, from whom we expect a report in the next quarter. The other was frozen in liquid nitrogen for cryostat sectioning. This will be carried out in case the block sent to CVD does not process well, and so that enzyme staining can be conducted to look at possible changes in fiber types. Results of histological analysis will be available in the final report.

Table 1: Implantation Schedule

Location and Types of Devices									
Cat	**Time (days)**	**Polyethylene Rod (neg control)**	**Uncoated BIONs**			**Coated BIONs**		**Silicon Rods (Neg control)**	
1	30	paraspinal	Paraspinal	MG	TA	paraspinal	-	paraspinal	-
2	30	paraspinal	Paraspinal	MG	TA	paraspinal	-	paraspinal	-
3	30	paraspinal	Paraspinal	MG	TA	paraspinal	-	paraspinal	-
4	30	paraspinal	Paraspinal	soleus	TA	paraspinal	-	paraspinal	-
5	90	paraspinal	Paraspinal	MG	TA	paraspinal	soleus	paraspinal	MG
6	90	paraspinal	Paraspinal	MG	TA	paraspinal	MG	paraspinal	soleus
7	90	paraspinal	Paraspinal	MG	TA	paraspinal	MG	paraspinal	soleus
8	90	paraspinal	Paraspinal	soleus	TA	paraspinal	MG	paraspinal	MG
9	180	paraspinal	Paraspinal		TA	paraspinal	-	paraspinal	-
10	180	paraspinal	Paraspinal		TA	paraspinal	-	paraspinal	-
11	180	paraspinal	Paraspinal		TA	paraspinal	-	paraspinal	-
12	365	paraspinal	Paraspinal		TA	paraspinal	-	paraspinal	-
13	365	paraspinal	Paraspinal		TA	paraspinal	-	paraspinal	-
14	365	paraspinal	Paraspinal		TA	paraspinal	-	paraspinal	-
Total Devices		**14** **Polyethylene Rods**	**36** **Non-coated BIONs**			**18** **Coated BIONs**		**18** **Silicon Rods**	

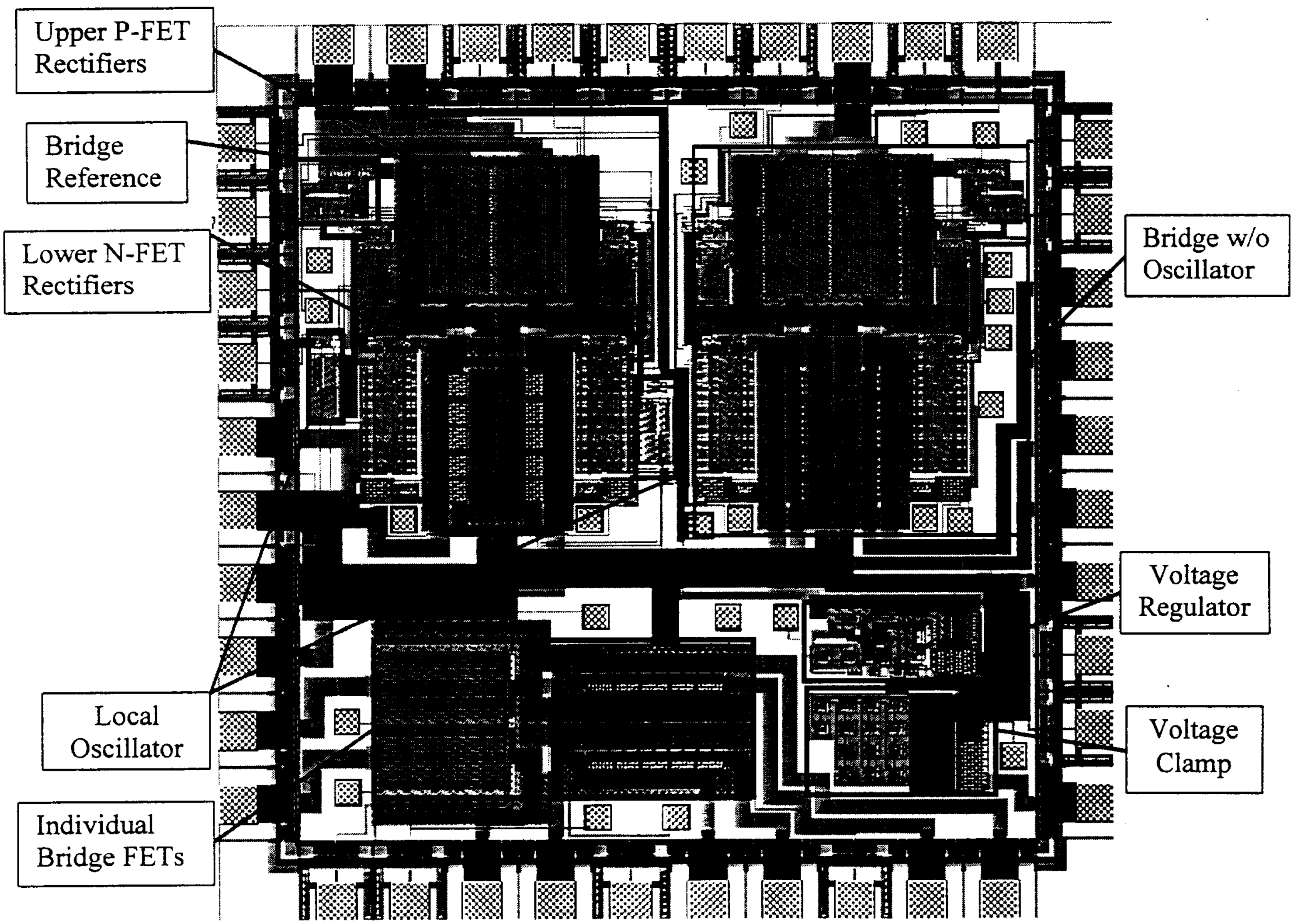
Chronic In vitro Testing at Queen's University

The last remaining glass-encapsulated BION (using PtIr tube-to-glass bead seal) on chronic test failed abruptly after 286 days of continuous output at maximum rated levels (10 mA x 258 microsec x 50 pps) while temperature cycling in isotonic saline (3 hr. @ 37C and 9 hr. @ 77C). Inspection showed that the test fixture had warped, jamming the Ir electrode against a recording electrode and cracking the PtIr tube to which the Ir electrode was welded. The BION had a large amount of water in the capsule confined to the Ir electrode end.

All external metal surfaces of the electrodes and feedthroughs were examined under the scanning electron microscope. The deep crack in the PtIr tube where it was welded to the Ir electrode was confirmed. A small region of the end of the PtIr tube had not completely melted during the final sealing process; machine marks were still visible with no signs of corrosion. The Ir electrode had the same surface that it tends to have after abrasive tumbling, with a few small regions where tumbling had not completely eradicated the tears left by the cutting process for making the Ir washer from foil. There were some amorphous deposits on the surface (probably salt or condensed leachate from the plastic test chamber) but no signs of corrosion of the metal. The tantalum electrode had the usual open porous structure produced by the sintering process, with no deposits or signs of corrosion.

During the last quarter work at the Pritzker Institute has focussed on analysis of MOS7 and refinement of the bi-directional rectifier and telemetry system.

In a previous report we described our difficulties in eliminating the parasitic bipolar transistors which produced a drain on the power supply when the lower rectification elements conducted into the substrate. MOS7 used a new guard band structure and synchronous rectification on the lower bridge elements to avoid this problem. In addition we included a local oscillator to test the reverse telemetry. A layout of MOS7 appears below with sections of the circuit identified.



Included on MOS7 were two bridge designs, one with an oscillator and one without, individualized bridge FETs, a voltage regulator, and a voltage clamp. Around the rectifying transistors used in the bridges, the guard ring structure described in our last QPR was used.

We evaluated the effectiveness of our strategy to eliminate the parasitic bipolar action by performing a series of curve tracer measurements upon the MOS7 bridge circuits. We were clearly able to see the combined effects of the synchronous rectification as well as the guard bands. When we disabled the drive to the lower N-FETs, the horizontal bipolar transistors turned on and pulled excessive current from the power supply. With the drive activated, the forward drop on the N-FET was significantly less than that required to forward bias the base-emitter junction of the bipolar. Therefore there was no parasitic current pulled from the power supply. With this success, we have contemplated variations on this structure to reduce the size of the rectifier transistors, as well as change the type to all N-FETs. Using N-FETs for the lower and UPPER rectifiers will eliminate the need for the floating N-Well of the upper P-FET transistors. This in turn will eliminate the need for the extensive guard band structure. We have already fabricated an all N-FET bridge, as part of another program, and we will be evaluating its performance during the next quarter.

In addition to the tests on the rectifiers, we also performed tests on the clock recovery circuit, the input demodulator, and the local oscillator.

The clock recovery circuit performed as expected. MOS7 uses a high-gain amplifier to recover the clock from the voltage on the micro-coil. The clock recovery performed very well, producing a solid clock signal even for input voltage which were well-below that needed for the rectification.

The input demodulator also performed as expected. Carrier dropouts of as few as one cycle could be detected. This is very encouraging and we will be expanding our testing of the data detection within the next quarter. During that time we will establish the smallest number of carrier cycles which we could use for a state change in the suspended carrier modulation scheme.

The local oscillator exhibited a problem related to bias. Under certain conditions the oscillator would stop and would require a transient to re-start. We have analyzed this problem in simulation and have revised our oscillator circuitry to include a more complicated, but a more robust transconductance amplifier. This new design will be implemented in MOS8. Fortunately we were able to revise MOS7 into MOS8 for submission during this quarter. We expect to receive MOS8 back from MOSIS during the next quarter.

At a much lower level, we have continued to work with the Mann Foundation to quantify the characteristics of the existing AMI 2-MHz microstimulator ASICs so that we may design a suitable 2-MHz transmitter.

2-MHz Microstimulator ASIC Development at AEMF

During this quarter, we received improved ASICs from MOSIS. These chips had corrections to three known problems: A floating node in the logic was fixed, an oscillation due to high voltage breakdown in the voltage regulator was corrected, and a layout error which injected noise into a sensitive node in the detector circuit was fixed. The chips were shorter than normal to allow them to fit on a lower cost MOSIS reticle.

Using chips bonded in normal integrated circuit DIP packages, the basic functionality of the chips was verified. After lapping the chips to reduce their thickness, electronic assemblies complete with coils were assembled. (Small shims of silicon were used to fill the gaps left by the shorter than usual chips.)

The reduced power supply filter capacitance dictated by the shorter chips did not cause any apparent problems. In reviewing data from the chip foundry, we found that the expected defect density in the capacitors is about 30 per square centimeter, so that having too large a capacitor will noticeably decrease yield. Because of this, we will probably keep the smaller capacitor value (and area) even when we extend the chip back to its (mechanically desirable) full length with non-MOSIS foundry runs.

Testing of the assemblies showed that the new chips work quite well, allowing compliance voltages of up to 17 volts. Signal detection worked over a wide range of input signal strength, and the power supply oscillation problems were gone. Yield in making these assemblies was disappointing, though. Many units passed intermediate tests up to the point of attaching the ferrites cores and winding the coils, but failed thereafter. Apparently, something in that process damaged the chips, but it was not clear why the damage did not appear in assemblies made with previous chips. A concentrated effort is now in progress to determine the cause of this problem. It should be easy to find out since it occurs between two well defined process steps.